# Early formed astrophysical objects and cosmological antimatter

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**Abstract**

Astronomical observations of recent years show that the universe at high redshifts about ten is densely populated by the early formed objects: bright galaxies, quasars, gamma-bursters, and contains a lot of metals and dust. Such rich early formed varieties have not been expected in the standard model of formation of astrophysical objects. There is serious tension between the standard theory and observations.We describe the model which naturally relaxes this tension and nicely fits the data. The model naturally leads to creation of cosmologically significant antimatter which may be abundant even in the Galaxy. Phenomenological consequences of our scenario and possibility of distant registration of antimatter are discussed.

# 1   Introduction

Probably the most impressive prediction of quantum field theory is the prediction of antimatter. Antiparticles are predicted and observed in experiment, but it is unknown if antimatter, i.e. antistars, antiplanets, antigalaxies exist anywhere in the universe. Presently cosmological antimatter (the real one not just antiparticles) is actively searched for by several groups and more sensitive detectors are proposed for future observations.

In his famous work [1], P.A.M. Dirac, predicted "with the tip of his pen" a whole world of antimatter (not just a small planet). He assumed initially that positively charged "electron" was proton!? Critics by Oppenheimer, who noticed that hydrogen would be unstable if proton was a hole in negative continuum, forced Dirac to conclude that "anti-electron" is a *new* particle with the same mass as the electron (1931). At that time a hypothesis about a new particle was not as blameless as today.

Very soon after that, in 1933, Carl Anderson announced the discovery of the positron, which was awarded by Nobel prize in 1936. According to the Anderson's words: it was not difficult, simply nobody looked for that.

Paul M. Dirac justly got his Nobel prize in 1933 immediately after the Anderson's discovery. In his Nobel lecture "Theory of electrons and positrons" (December 12, 1933) Dirac, in particular, said "If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system) contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half of stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods." However, as we see in what follows, now we know ways to distinguish a stars from an antistars by observations from the Earth. The spectra are not exactly the same, even if CPT is unbroken and polarization of the electromagnetic radiation or the type of emitted neutrinos/antineutrinos from supernovae can be good indicators to a star made of antimatter.

It is striking that Dirac was the second person to talk about antimatter. In 1898, 30 years before Dirac and one year after the discovery of electron (J.J. Thomson, 1897) Arthur Schuster (another British physicist) conjectured that there might be other sign electricity, *antimatter*, and supposed that there might be entire solar systems, made of antimatter, *indistinguishable* from ours.

In his paper "Potential Matter. Holiday Dream" [2] A. Schuster wrote "When the year's work is over and all sense of responsibility has left us, who has not occasionally set his fancy free to dream about the unknown, perhaps the unknowable?" and later "Astronomy, the oldest and yet most juvenile of the sciences, may still have some surprises in store. May antimatter be commended to its case".

Schuster made one more fantastic and correct guess. He envisaged that matter and antimatter are capable to annihilate and to produce *vast* energy. Remember that this was done before Einstein established his famous relation between mass and rest energy, $E = mc^2$.

To eliminate antimatter in close vicinity to the Earth Schuster conjectured that

matter and antimatter are gravitationally repulsive because antimatter has negative mass. Two such objects on close contact should have vanishing mass. As we know now, all that happened to be incorrect: matter and antimatter are gravitationally attractive and and masses of particles and antiparticles has the same sign, and, due to the CPT-theorem, their masses are equal by magnitude. Presently we have other explanations why antimatter is not seen in our neighborhood. Moreover, as we argue in what follows, abundant stellar-like antimatter objects may be hidden even in the Galaxy not far from the Earth. Other galaxies may be also abundant with antimatter.

It would be great if these two great prophets were right and anti-worlds do exist. However, the standard, simplest approach to baryogenesis (Sakharov) leaves no room for anti-worlds. Still simple generalization of baryogenesis scenarios could lead to abundant anti-worlds. Very early formed and/or too old astronomical objects, observed presently, especially during last few years, may signify an existence of antiworlds.

An observation of cosmic antimatter will give a clue to physics of baryogenesis, to the mechanism of cosmological C and CP breaking, and present an extra argument in favor of inflation. Since generalized scenarios predict not just a single number of baryon to photon ratio, $\beta = (N_B - N_{\bar{B}})/N_\gamma$, but a whole function of space point, $\beta(x)$, the models are falsifiable.

# 2 Traditional ways of antimatter search and observational bounds

There are essentially two main methods for search of cosmic antimatter used up to now. The first, older one, is a registration of the the products of $e^+e^-$ and $\bar{p}p$ annihilations into electromagnetic radiation. In the first case especially spectacular is 0.511 MeV line from $e^+e^-$-annihilation at rest, which is in fact observed in the Galactic center, but its origin is still unclear. Proton-antiproton annihilation would create $\sim 100$ MeV photons with rather wide spectrum resulting from the decays of pions originally created by the annihilation.

A registration of excessive cosmic antiprotons and positrons at low energies could also be an indication for antimatter but at the present time the flux of low energy antiprotons and positrons can be explained by the conventional mechanism.

These are of course indirect methods and even if excessive antiprotons, psitrons, or gamma-rays are observed, a further analysis is necessary to exclude traditional mechanisms of their production.

Even less direct methods include an analysis of spectrum distortion of the CMB (both frequency and angular fluctuations), of the impact of antimatter on big bang nucleosynthesis (BBN), and f the large scale structure formation.

During the last decade there is a burst of experimental activity for direct search of cosmic antimatter, namely for the search of antinuclej in cosmic rays, which have negligible probability to be secondary-produced in the universe. There are presently the following missions for the direct search of cosmic antinuclej:

1. BESS: Japanese Balloon Borne Experiment with Superconducting Solenoidal Spectrometer.

2. PAMELA (Italian-Russian space mission): Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics.

3. AMS: AntiMatter Spectrometer (Alpha Magnetic Spectrometer), CERN-MIT-NASA.

The following two, more sensitive, detectors are under discussion now:

PEBS (Positron Electron Balloon Spectrometer,) search for cosmic positrons and antiprotons.

GAPS (Gaseous Antiparticle Spectrometer), search for X-rays from de-excitation of exotic atoms, it may reach 2 orders of magnitude better sensitivity than AMS for the ratio $\bar{H}e/He$.

At the present time the following bound on the flux of the antihelium-4 in cosmic rays is found : BESS: $\bar{H}e/He < 3 \times 10^{-7}$. More restrictive limits are expected: PAMELA: $\bar{H}e/He < 3 \times 10^{-8}$; AMS-2: $\bar{H}e/He < 10^{-9}$ but not yet reported. The fluxes above are normalized to the observed flux of the cosmic ray helium which at $E < 10$ GeV/nuclei is equal to:

$$dN_{He}/dE = 10^2/\mathrm{m}^2/\mathrm{str}/\mathrm{sec}/\mathrm{GeV}. \tag{1}$$

According to the calculations of ref. [3] the expected fluxes of the secondary produced anti-nuclei are the following. Anti-deuterium is produced in $\bar{p}p$ or $\bar{p}He$ collisions The predicted flux of anti-deuterium produced by this mechanism is $\sim 10^{-7}/m^2/s^{-1}/sr/(GeV/n)$, i.e. 5 orders of magnitude lower than the observed flux of antiprotons. The expected fluxes of secondary produced $^3\bar{H}e$ and $^4\bar{H}e$ are respectively 4 and 8 orders of magnitude smaller than the flux of anti-D.

Observations and bounds, summary:

$\bar{p}/p \sim 10^{-5} - 10^{-4}$, is observed and can be explained by secondary production;

observed $He/p \sim 0.1$; the upper limit: $\bar{H}e/He < 3 \times 10^{-7}$.

Theoretical predictions: $\bar{d} \sim 10^{-5}\bar{p}$, $^3\bar{H}e \sim 10^{-9}\bar{p}$, $^4\bar{H}e \sim 10^{-13}\bar{p}$.

From the upper limit on $\bar{H}e$: the nearest single antigalaxy should be at the distance larger than 10 Mpc (very crudely).

Production of antinuclej was studied at LHC at ALICE detector [4]. According to its data the production of an antinucleous with an additional antinucleon is suppressed only by factor about 1/300 which is by far milder than the suppression factors presented above. Probably the difference is related to much higher energies at which data of ALICE are taken. The events with such energies are quite rare in cosmic rays and do not have significant impact on the total rate of the antinuclej production.

Traditional bounds of the amount of the cosmic antimatter derived from the fluxes of the cosmic gamma rays did not change during the last few decades because they essentially valid to our galactic supercluster. According to ref. [5] the nearest anti-galaxy could not be closer than at ∼10 Mpc, as follows from the analysis of $\bar{p}p$-annihilation in common intergalactic cloud. The raction of antimatter in colliding galaxies in Bullet Cluster is bounded from above by $< 3 \times 10^{-6}$ [6].

Note that CMB excludes *large* isocurvature fluctuations at distances $d > 10$ Mpc and BBN excludes large "chemistry" fluctuations at $d > 1$ Mpc. It means in particular that in a simple model the antimatter domains or objects should be sufficiently small.

There is relatively recent bound on the amount of antistars in the galaxy [7]. The Bondi accretion of the interstellar gas to the surface of an antistar leads to the

annihilation luminosity:

$$L_\gamma \sim 3 \cdot 10^{35} (M/M_\odot)^2 v_6^{-3} \tag{2}$$

It allow to put the limit $N_{\bar *}/N_* < 4 \cdot 10^{-5}$ inside 150 pc from the Sun, where $M$ is the mass of the star, $M_\odot$ is the solar mass, and $v_6$ is the star velocity in $10^6$ cm/sec.

Note in conclusion that all the presented bounds are true if antimatter makes the same type objects as the *observed* matter ones. For example, as we show in what follows, compact fast antistars may be abundant in the Galaxy but still escape observations. A recent analysis of bounds on different type of antimatter objects was performed in ref. [8]. Earlier works on cosmology with domains of matter and antimatter was discussed in the lectures [9], where a list of relevant references can be found.

# 3    Observations of antistars from the Earth

According to Dirac and Schuster cited in the Introduction, antistars are indistinguishable from stars by astronomical observations. The basis for that is the CPT theorem, though it was unknown to the both quoted persons. This theorem demands equality of the level positions in atoms and antiatoms, so spectral measurements at first sight do nor allow to distinguish if the light is emitted by an atom or an antiatom. However, we will see below that this is not exactly true.

Of course if CPT is broken, the masses of particles and antiparticles may be different, though it is not necessarily so. If the particle-antiparticle mass difference is non-zero, $\Delta m \neq 0$, the spectra of anti-atoms might be different in an irregular way, not described by the redshift. However, even if $\Delta m \neq 0$, it must be extremely tiny. As it is argued in ref. [10], non-zero mass difference between, say, electron and positron or between proton and antiproton breaks gauge invariance of electrodynamics, which in turn leads to non-zero photon mass. The upper bounds on the latter are extremely restrictive and they demand very strong upper bounds on the mass difference $\Delta m_{ee} \equiv |m_e - m_{\bar e}| < 2 \cdot 10^{-17}$ eV or even $\Delta m_{ee} < 4 \cdot 10^{-29}$ eV [10]. So even if $\Delta m_{ee} \neq 0$, its effect on the spectrum should be tiny.

Below we assume that CPT is respected and show that there are still chances for distant observation of antiworlds.

Since C and CP are broken, the widths of spectral lines of atoms and anti-atoms must be different [11]. Unfortunately the magnitude of the effect for hydrogen is extremely small, maybe because of an accidental cancelation:

$$\Delta\Gamma/\Gamma \sim 10^{-28}. \tag{3}$$

An amplification of the effect, in particular, in heavier atoms and in external magnetic or electric fields might be possible.

Possibilities discussed in ref. [12] look much more realistic, One evident way is to establish radio communication with inhabitants of the stellar system under scrutiny.. It may help to determine if they are or are not antimatter creatures. It is possible but looks more proper for science fiction.

A perspective way, maybe even in not too distant future, is a study of stellar neutrinos versus antineutrinos, especially from energetic SN explosions. At the first

stage of SN explosion neutrinos from the neutronization reaction $pe^- \to n\nu$ are emitted, while an anti-SN would emit antineutrinos.

An interesting possibility is a search for antistars through detection of polarized photons produced in weak interaction processes. These photons are longitudinally polarized and their energy can be well defined if they are created in two body decays. Mono-energetic photons produced e.g. in $B \to K^\star \gamma$ should be left-handed because of dominance of $b \to s\gamma$ penguin transition with left-handed $s$-quark. However, one can hardly expect noticeable abundance of B-mesons in stars, and most probably there is an equal amount of $B$ and $\bar{B}$ mesons.

Stars with abundant strange quarks look more promising. The outer shell of such stars is populated by $\Sigma$-hyperons and the polarization of photons emitted in $\Sigma^+ \to p\gamma$ decay could indicate if the photons are emitted by hyperon or anti-hyperon. The polarization is large, $\alpha = -0.76 \pm 0.08$ and the branching ratio is non-negligible $(1.23 \pm 0.05) \times 10^{-3}$.

Circular polarization of photons in the $\gamma$-transitions of nuclei was observed in the terrestrial experiments: $P_\gamma = (4 \pm 1) \cdot 10^{-5}$ in $^{175}Lu$ transition with the emission of 395 keV photon, $P_\gamma = -(6 \pm 1) \cdot 10^{-6}$ for 482 keV photon emitted in $^{181}Ta$ transition, and $P_\gamma = (1.9 \pm 0.3) \cdot 10^{-5}$ for 1290 keV photon emitted in transition of $^{41}K$. Measurement of circular polarization of such photon lines is ideally suited for search of antistars.

# 4  Baryogenesis

Prevailing point of view at the present time is that all the universe is made only of matter, while primeval antimatter is absent. Still the fact that antimatter exists creates fundamental cosmological puzzle: why the observed universe is 100% dominated by matter? Antimatter exists but not antiworlds, why? The problem deepened because of approximate symmetry between particles and antiparticles. In fact before 1956, the common faith in exact C, P, and T symmetries looked unbreakable, but with passing years more and more out of these discrete symmetries were discovered to be broken.

The puzzle of the baryon asymmetry, i.e. of the observed predominance of matter over antimatter is resolved by three Sakharov's principles [13]:
I. Nonconservation of baryons.
II. Violation of symmetry between particles and antiparticles, i.e. C and CP.
III. Breaking of thermal equilibrium.

There is a plethora of baryogenesis scenarios which can explain the single number:

$$\beta_{observed} = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \times 10^{-10} \,. \tag{4}$$

The usual outcome: $\beta = const$, which makes it impossible to distinguish between models and does not leave space for cosmological antimatter. But the situation is not so pessimisitc, a simple and natural generalizations of the simplest models of baryogenesis allow for a lot of antimatter almost at hand. Of all the models the particularly interesting one is the Affleck-Dime (AD) or supersymmetric baryogenesis [14]. It is the only known scenario of baryogenesis which may create large baryon

asymmetry, $\beta \sim 1$, while all other models are able to create only a very small $\beta$, so theoretical efforts are usually done to enhance the asymmetry as much as possible to make it compatible with the observed value.

Supersymmetry (SUSY) predicts existence of scalar bosons with non-zero baryonic number, $B \neq 0$. Such bosons may condense along flat directions of the quartic potential, which is a generic property of the potential in such models:

$$U_\lambda(\chi) = \lambda|\chi|^4 \left(1 - \cos 4\theta\right), \tag{5}$$

There can be also the mass term, $m^2\chi^2 + m^{*2}\chi^{*2}$, which has another set of flat directions:

$$U_m(\chi) = m^2|\chi|^2[1 - \cos(2\theta + 2\alpha)]. \tag{6}$$

where $\chi = |\chi|\exp(i\theta)$ and $m = |m|\exp(\alpha)$. If $\alpha \neq 0$, C and CP are broken.

In grand unified (GUT) SUSY models the baryonic number of $\chi$ is naturally non-conserved. It is expressed by the non-invariance of $U(\chi)$ (5, 6) with respect to the phase rotation, $\chi \rightarrow \exp(i\theta)\chi$.

Initially (at inflation) $\chi$ is naturally away from the origin and when inflation is over, it starts to evolve down to the equilibrium point, $\chi = 0$, according to the equation of Newtonian mechanics for point-like particle:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0. \tag{7}$$

Baryonic charge of $\chi$:

$$B_\chi = \dot{\theta}|\chi|^2 \tag{8}$$

is analogous to the mechanical angular momentum in the two-dimensional complex plane $[Re\,\chi,\ Im\,\chi]$. The decays of $\chi$ transferred the baryonic charge accumulated in the rotational motion of $\chi$ into that of quarks in B-conserving processes.

If $m \neq 0$, the angular momentum, or what is the same the baryonic number, B, is generated by possibly different directions of the quartic and quadratic valleys at low $\chi$. If CP-odd phase $\alpha$ is small but non-vanishing, both baryonic and antibaryonic regions are possible with dominance of one of them. Matter and antimatter domain may exist but globally $B \neq 0$. This is briefly the canonical version of the AD-scenario which results in normal value of the baryon asymmetry with possible domains of antimatter of arbitrary sizes and values of $\beta$. Such a model of antimatter creation is strongly restricted by the observational data.

A minor modification of AD-scenario can lead to very early formation of compact stellar-type objects and naturally to a comparable amount of anti-objects, such that the bulk of baryons and (equal) antibaryons are in the form of compact stellar-like objects, e.g. QSO or primordial black holes (PBH), formed in the regions with a huge baryon asymmetry, plus sub-dominant observed homogeneous baryonic background. The amount of antimatter may be comparable or even larger than of *known* baryons, but such "compact" (anti)baryonic objects would not contradict any existing observations.

Note that the astronomical data accumulated during the last few years demonstrate rich population of superheavy black holes in the very early universe, which indeed could be created in the frameworks of the modified AD-scenario, but remain mysterious otherwise,

The necessary generalization of the AD-baryogenesis was suggested in ref. [15] and further developed in ref. [16]. To this end a general renormalizable coupling of the Affleck-Dine field $\chi$ to inflaton, $\Phi$, has been introduced (the first term in the equation below), so the total potential of $\chi$ included the interaction with the inflaton, $\Phi$, gets the form:

$$ U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4| \ln\left(\frac{|\chi|^2}{\sigma^2}\right) + \lambda_1\left(\chi^4 + h.c.\right) + (m^2\chi^2 + h.c.). \qquad (9) $$

The second term in this expression is the so called Coleman-Weinberg [17] potential obtained by summation of one-loop radiative corrections.

When $\Phi$ is far from $\Phi_1$, the effective mass squared of $\chi$ is positive and large, so the gate to the flat directions is closed. It is open only during relatively short period, when $\Phi \approx \Phi_1$, but still at inflationary epoch. Because of that cosmologically small but possibly astronomically large bubbles with very high $\beta$ could be created, occupying a small fraction of the universe volume, while the rest of the universe has the normal baryon asymmetry $\beta \approx 6 \cdot 10^{-10}$, created in the regions with small initial $\chi$, occupying the bulk of the universe volume. Such process looks as phase transition of $3/2$ order. In the simplest version of the model the high-$\beta$ objects would have positive and negative baryon asymmetry with practically equal probability. Interesting anti-objects should be astronomically large, so inflation is necessary and not too large to avoid problems with the existing observations. So some, rather mild fine-tuning of the model parameter values is necessary.

The distribution of high baryon density bubbles over mass (and size) has very simple log-normal form:

$$ \frac{dN}{dM} = C_M \exp\left[-\gamma \ln^2(M/M_0)\right] \qquad (10) $$

where $C_M$, $\gamma$, and $M_0$ are constant model dependent parameters. The spectrum is practically model independent, because it is essentially determined by the exponential expansion (inflation).

There are several (essentially two) periods when the density contrast between the regions with high baryonic density and those with the normal low one arose:
1. Firstly, after formation of the domains (bubbles) with high value of $\chi$ and correspondingly with huge baryon (anti-baryon) asymmetry the initial density contrast between the high-B bubbles and the rest of the universe would be zero or very small, because quarks, which carry baryonic number at this stage were massless. These are the so called isocurvature perturbations. Somewhat later due to different equations of state inside and outside of the domains (or what is the same of high-B bubbles) some density contrast would evolve because the matter inside the bubbles were more non-relativistic due to higher amplitude of non-relativistic field $\chi$ inside.
2. The second period of perturbation rise is much more efficient. It takes place after the QCD phase transition at $T \sim 100$ MeV when quarks made non-relativistic protons. During this stage compact bubbles with high baryonic mass density would be formed. With properly chosen parameters such bubbles could be primordial black holes (PBHs), or dense stellar like objects. The PBH masses could range from a few $M_\odot$ up to $10^{6-7}M_\odot$.

The model successfully explains quite a few mysterious facts observed by astronomers, with the data especially accumulated during the recent few years. It

presents a mechanism of superheavy black hole formation, and what is especially important, at very early time. Correspondingly it explains existence of quasars observed at high redshifts, $z \sim 10$, which is mysterious in the standard model. Moreover, the near-quasar space is enriched with metals. An explanation of this fact demands an unusual BBN (see below) or an early supernova formation. High redshift gamma bursters also demand early cleated supernovae - this can be simply arranged in the considered model. Early formed superheavy BHs can be seeds of galaxy formation. In the accepted nowadays picture the process is supposed to be the opposite: first galaxies were formed and superheavy BHs in the center of practically all observed galaxies were created later by the matter accretion to the galactic center. However, in the standard approach the rate of superheavy BH formation is too low to explain their formation during the cosmological time. Moreover, several small galaxies are known with the central superheavy BH having mass similar by magnitude to the total mass of the galaxy. This surely does not fit the standard accretion picture.

*BBN in high-B environment.* If $\beta \equiv \eta \gg 10^{-9}$, light (anti)element abundances would be anomalous: the clouds with high $\beta$ would contain much less (anti)deuterium and more (anti)helium, than the normal one. Evolved chemistry in the so early formed QSOs can be explained, at least to some extend, by more efficient production of metals during BBN due to much larger ratio $\beta = N_B/N_\gamma$. The standard BBN essentially stops at $^4$He because of the very small $\beta$. However, in the model considered here $\beta$ is much larger than the canonical value, even being close or exceeding unity. BBN with anomalously high $\beta \gg \beta_{obs} = 6 \cdot 10^{-10}$ was considered in ref. [18] but still only up to $\beta \ll 1$. An extension to $\beta \sim 1$ would be very interesting.

To summarize the model explains in the unique way the formation of high-redshift supernovae, gamma-bursters, stars older than the universe observed in the Milky Way, cut-off BH distribution at $M < 6M_\odot$ in galaxies, and more. It is discussed in detail in the next section.

According to our estimates the compact anti-objects mostly survived in the early universe, (especially if they are PBHs). The model predicts an existence of a kind of early dense stars formed when the initial pressure outside was larger than internal pressure. Astrophysics of such objects may be quite unusual. Such "stars" may evolve quickly and, in particular, make early SNs, enrich the universe with heavy (anti)nuclei and reionize the universe.

Phenomenology and bounds on compact antimatter objects and disperse anti-clouds was studied in the papers [19, 8]. The early formed stars and black holes are discussed in ref. [20]

# 5 Mysteries in the sky

On the background of quite successful description of the gross features of the universe the standard $\Lambda$CDM cosmology encounters plenty of disturbing and interesting problems. These troubling data became especially prominent during the last several years. In short, there is an avalanche of astronomical discoveries of different kind of astrophysics objects which could not be created and evolved in the available cosmological time. They are observed in the very early universe at redshifts $z \sim 10$ and in the contemporary universe, e.g. in our Galaxy there are stars, which look older

than the universe. Rephrasing the famous words by Marcellus from "Hamlet" we can say: "Something is rotten in the state of ~~Denmark~~ the Universe". It is tempting to explain all these data by our model described in the previous section. It is especially interesting that the suggested scenario predicts, as a byproduct abundant cosmological antimatter in close vicinity to the Earth.

To see how old are the objects observed at different redshifts let us present the expression of the universe age $t_U$, as a function of the cosmological redshift $z$:

$$t(z) = \frac{1}{H} \int_0^{1/(z+1)} \frac{dx}{\sqrt{1 - \Omega_{tot} + \Omega_m/x + x^2\,\Omega_v}}, \tag{11}$$

where $\Omega_m$ is the fractional (in terms of the critical energy density) energy density of matter (i.e baryonic plus dark matter), and $\Omega_v$ is the fraction of the density of dark energy. The total fraction of the cosmological energy density, $\Omega_{tot}$, is supposed to be unity (spatially flat universe), since the energy density of the CMB photons and neutrino can be neglected during essential time interval in the integral.

According to the Planck data, the present day values of theses parameters are: $\Omega_{tot} = 1$, $\Omega_m = 0.317$, and $\Omega_v = 0.683$. There is some tension between the values of the Hubble parameter measured by Planck, $H_{pl} = 67.3$ km/sec/Mpc and that measured by the traditional astronomical methods, which can lead to $H$ as large as $H_{astr} = 74$ km/sec/Mpc, see ref. [21] for discussion. Possibly both results might be correct and the difference in the measured values of $H$ emerges because the Planck and the astronomical measurements are sensitive to $H$ at different moments of the cosmological history. This e.g. can occur in a model where a fraction of dark matter is unstable and decays at some moment between the recombination and the present day [22].

We present a few examples of the universe age in giga-years for different $z$. The first number corresponds to the Planck measured value of $H$, and the other, shorter one, in brackets to the larger astronomical value: $t_U \equiv t(0) = 13.8\,(12.5.)$; $t(3) = 2.14\,(1.94)$; $t(6) = 0.93;\,(0.82)$; $t(10) = 0.47\,(0.43)$; and $t(12) = 0.37;\,(0.33)$.

## 5.1   Strange phenomena in the Milky Way.

*Old stars in the Milky Way.* With an increased accuracy of the nuclear chronology the ages of several stars have been recently determined to be much older than expected. Below we quote a few recent results.

Employing thorium and uranium abundances in comparison with each other and with several stable elements the age of metal-poor, halo star BD+17$^o$ 3248 was estimated as [23] $13.8 \pm 4$ Gyr. For comparison the age of inner halo of the Galaxy is $11.4 \pm 0.7$ Gyr.

The age of a star in the galactic halo, HE 1523-0901, was estimated to be about 13.2 Gyr[25]. First time many different chronometers, such as the U/Th, U/Ir, Th/Eu and Th/Os ratios to measure the star age have been employed.

The metal deficient *high velocity* subgiant in the solar neighborhood HD 140283 has the age $14.46 \pm 0.31$ Gyr [26] The central value exceeds the universe age by two standard deviations, if $H = 67.3$ and $t_U = 13.8$, while for $H = 74$, and thus $t_U = 12.5$ the excess is by nine standard deviations. So this could really looks as a star older than the universe.

A possible explanation of this discrepancy could be an unusual initial chemical content of such stars. Normally a pre-stellar cloud consists of 25% of $He^4$ and 75% of hydrogen. However, in our case the primordial nucleosynthesis is able to create much heavier elements, as is mentioned in the previous sections or/and the early supernovae could enrich the interstallar gas with heavy elements, so the initial chemical content of some stars would be much different from the traditional one. Such stars could evolve to their present state considerably faster than the usual ones. Of course this conjecture should be verified by the stellar nucleosynthesis calculations.

*The mass distribution of BHs* observed in the Milky way demonstrates some peculiar features not understood by the conventional theory. It is found that their masses are concentrated in the narrow range $(7.8 \pm 1.2)M_\odot$ [27]. This result agrees with another paper where a peak around $8M_\odot$, a paucity of sources with masses below $5M_\odot$, and a sharp drop-off above $10M_\odot$ are observed [28]. Such facts are indeed very strange, if these BHs were formed by the stellar collapse, as it is usually assumed. However the log-normal mass distribution (10) of the primordial black holes naturally explains such a form of the mass spectrum of the stellar mass black holes in the Galaxy. Astronomical data also indicate a two-peak mass distribution of the PBHs and compact stars, which is probably observed, but not explained up to now [29]. Quoting this work: "sample of black hole masses provides strong evidence of a gap between the maximum neutron star mass and the lower bound on black hole masses". These results also fit the mass distribution of our model, assuming that the neutron stars were mostly created by the conventional mechanism.

## 5.2 Supermassive BHs and quasars in (near) contemporary universe

it seems that every large galaxy and some smaller ones contain a central supermassive BH with masses larger than $10^9 M_\odot$ in giant elliptical and compact lenticular galaxies and $\sim 10^6 M_\odot$ in spiral galaxies like Milky Way.

The mass of BH is typically 0.1% of the mass of the stellar bulge of galaxy [30] but some galaxies may have huge black holes: e.g. NGC 1277 has the central BH of $1.7 \times 10^{10} M_\odot$, or 60% of its bulge mass [31]. This fact creates serious problems for the standard scenario of formation of central supermassive BHs by accretion of matter in the central part of a galaxy. An inverted picture looks more plausible, when first a supermassive black hole was formed and attracted matter serving as seed for subsequent galaxy formation.

More similar examples can be found in ref. [32]. As the authors say, although supermassive black holes correlate well with their host galaxies, there is an emerging view that outliers exist. Henize 2-10, NGC 4889, and NGC1277 are examples of super massive black holes at least an order of magnitude more massive than their host galaxy suggests. The dynamical effects of such ultramassive central black holes is unclear.

A discovery of an ultra-compact dwarf galaxy older than 10 Gyr, enriched with metals, and probably with a massive black in its center also seems to be at odds with the standard model [33]. The dynamical mass of the galaxy is $2 \times 10^8 M_\odot$ and the radius is $R \sim 24$ pc, so its density is very high. The Chandra data reveal a variable central X-ray source with $L_X \sim 10^{38}$ erg/s that could be an active galactic

nucleus associated with a massive black hole or a low-mass X-ray binary. Analysis of optical spectroscopy shows the object to be old, $\gtrsim 10$ Gyr and of solar metallicity, with elevated [Mg/Fe] and strongly enhanced [N/Fe] that indicates light element self-enrichment; such self-enrichment may be generically present in dense stellar systems.

Recently an observation of a quasar quartet embedded in giant nebula was reported [34] in a survey for Lyman- emission at redshift $z \approx 2$. According to the authors, it reveals rare massive structure in distant universe. All galaxies once passed through a hyperluminous quasar phase powered by accretion onto a supermassive black hole. But because these episodes are brief, quasars are rare objects separated by cosmological distances, so the chance of finding a quadruple quasar is $\sim 10^{-7}$. It implies that the most massive structures in the distant universe have a tremendous supply ($\sim 10^{11} M_\odot$) of cool dense ($n \approx 1/\text{cm}^{\mathbf{3}}$) gas, in conflict with current cosmological simulations.

## 5.3 Young objects at high redshifts

There is a large "zoo" of evolved astronomical objects formed in the universe in surprisingly short times. Several galaxies have been observed at high redshifts, with natural gravitational lens "telescopes". There is a galaxy at $z \approx 9.6$ which was formed when the universe was approximately 0.5 Gyr old [35].

Moreover a galaxy at $z \approx 11$ has been observed [36] which was formed eariler than the universe age was  0.41 Gyr (or even shorter with larger H).

An observation of not so young but extremely luminous galaxy was recently reported by WISE [40]: $L = 3 \cdot 10^{14} L_\odot$; age: $\sim 1.3$ Gyr. For creation of such galaxy the galactic seeds, or embryonic black holes, might be bigger than thought possible. As one of the authors of the paper, P. Eisenhardt, said : "How do you get an elephant? One way is start with a baby elephant." The BH was already billions of $M_\odot$ , when our universe was only a tenth of its present age of 13.8 billion years.

Thus we smoothly come to another and even more striking example of early formed objects, i.e. to quasars observed at high z. A quasar with maximum $z = 7.085$ has been observed [37]. It means that the quasar was formed at $t < 0.75$ Gyr. Its luminosity and mass are respectively $L = 6.3 \cdot 10^{13} L_\odot$ and $M = 2 \cdot 10^9 M_\odot$. The quasars are supposed to be supermassive black holes (BH)  and their formation in such short time looks problematic by conventional mechanisms.

As it is summarized in ref. [38] "rapid emergence of high-z galaxies so soon after the big bang may actually be in conflict with current understanding of how they came to be. This problem is very reminiscent of the better known (and probably related) premature appearance of supermassive black holes at $z \sim 6$. It is difficult to understand how $10^9 M_\odot$ black holes appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe."

Very recently another monster was discovered [39]: "An ultraluminous quasar with a twelve billion solar mass black hole at redshift 6.30". There is already a serious problem with formation mechanism of lighter and less luminous quasars which is now multifold deepened with this new "creature". As is stated in the paper, about 40 quasars with $z > 6$ are known, each quasar containing BH with $M \sim 10^9 M_\odot$. Such black holes, when the Universe was less than one billion years

old, present substantial challenges to theories of the formation and growth of black holes and the coevolution of black holes and galaxies. Now we have an order of magnitude heavier one, $M \approx 10^{10} M_\odot$. It has an optical and nearinfrared luminosity a few times greater than those of previously known $z > 6$ quasars.

As we have already mentioned, the universe at $z \sim 10$ is quite dusty, for a recent analysis and references see the paper [41]. The medium around the observed early quasars contains considerable amount of "metals" (elements heavier than He). According to the standard picture, only elements up to $^4$He and traces of Li, Be, B were formed in the early universe by BBN, while heavier elements were created by stellar nucleosynthesis and dispersed in the interstellar space by supernova explosions. If so, prior to or simultaneously with the QSO formation a rapid star formation should take place. These stars could produce plenty of supernovae which enriched interstellar space by metals.

Moreover, observations of high redshift gamma ray bursters (GBR) also indicate a high abundance of supernova at large redshifts. The highest redshift of the observed GBR is $z = 9.4$ and there are a few more GBRs with smaller but still high redshifts. The necessary star formation rate for explanation of these early GBRs is at odds with the canonical star formation theory.

On the other hand, our model may naturally lead to high density of compact stars, which in particular can be early supernova created much earlier than $z = 10$.

# 6   Conclusion

The observational data at high redshifts, $z \sim 10$, which became available in the recent years show that the universe is populated by the early formed bright galaxies, quasars, gamma-bursters, and contains a lot of metals and dust. Such rich early formed varieties have not been expected in the standard model of formation of astrophysical objects. There is serious tension between the standard theory and observations.

Probably most striking is existence of supermassive black holes both in the early and in the present day universe. The standard scenario is that such black holes have been formed through accretion of matter to an initial solar mass black hole. However, it demands much more time than that available during all the cosmological history. This is especially troubling for the supermassive black holes (quasars) created at the dawn of the universe at high $z$. The inverted picture when primordial BHs were first created and then served as seeds for the galaxy formation looks much more probable. Black holes found in small galaxies, having masses about half of the total galaxy mass surely cannot be created by the conventional mechanism.

The model [15], suggested almost a quarter of century ago, very nicely fits all the new observations, at least qualitatively. Of course more detailed quantitative work is necessary. A natural, though not obligatory, outcome of this model is a prediction of cosmic antimatter, mostly in the form of compact high velocity stars in the Galaxy. The observational bounds on the abundance of such stars are quite vague, so we may have a lot of antimatter practically at hand. Such early formed stars would behave as cold dark matter and so should have much larger velocity than the normal stars and hence they would populate the galactic halo. The mysterious

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MACHOs [42] can be just such very early and almost non-luminous stars.

An observation of antistars in the Galaxy would present a very strong support of the suggested scenario. Since antimatter was created in clouds with the unusually high baryon-to-photon ratio $\beta$, the BBN in these clouds would produce anomalous abundances of light elements. So it may be helpful for discovery of cosmic antimatter to look firstly for the clouds with anomalous chemistry in the galaxy. Though with 50% probability it may be the normal matter with anomalous $n_B/n_\gamma$, there is a good chance that this region is made of antimatter and so it should be thoroughly investigated, especially by searching for gamma radiation produced by the matter-antimatter annihilation.

Another interesting feature of this model of antimatter formation is that heavy antinuclej, not only anti-$He^4$ can also be found in the cosmic rays. Their abundances could be similar to those observed in SN explosions.

# Acknowledgement

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